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The Evaluation of Actual Material Properties of Low Alloy CrMoV Steel from the Results of Small Punch Tests

Karel Matocha[a], Ladislav Kander[a], Ondřej Dorazil[a], Kaishu Guan[b], Yifen Xu[b]

[a]*Material &Metallurgical Research, Ltd., Pohraniční 693/31, 703 00 Ostrava-Vítkovice, Czech Rep.*
[b]*School of Mechanical Engineering, East China University of Science and technology, 130 Mwilong Rd., Shanghai 200237, China*

Abstract

The Small Punch (SP) test technique is used for the evaluation of actual tensile, fracture and creep characteristics of materials exposed for a long period in operating plant components in order to provide data needed for plant life and integrity assessment.
In the present paper the results of SP tests in the temperature range from -193°C to +20°C, carried out in two laboratories on low alloy steel of type 14MoV6-3 in as received state and after long term operation at 540°C were compared. SP transition temperatures T_{SP} determined from the temperature dependences of the fracture energy were correlated with the FATT temperatures obtained using standardized Charpy V notch test specimens.

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Keywords: SP test, load displacement curve, SP transition temperature T_{SP}, SP fracture energy E^{SP}, FATT, empirical correlation

1. Introduction

Both European Code of Practice [1] and Chinese Code of Practice [2, 3] give a guidance on the procedure to be followed when carrying out Small Punch tests aimed at evaluation of tensile and fracture behavior of materials exposed in operating plant components in order to provide data needed for plant life and integrity assessment. In 2012 the solution of bilateral project, focused on the comparison of Codes of Practice for determination of mechanical properties by SP tests between EU and China, was initiated in the frame of Czech-Chinese Scientific and Technological Cooperation. The participants of the project were MATERIAL & METALLURGICAL RESEARCH Ltd. (MMR), Ostrava, Czech Rep. and School of Mechanical Engineering, East China University of Science and Technology, Shanghai, China (SME). On the basis of common experimental programme realized in both laboratories the database of results of standardized tensile and impact tests and the SP tests results in the temperature

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range -193°C - +20°C were obtained. The objective of the common experimental programme realized on low alloy steel of type 14MoV6-3 in as received state and after long term exposition at 540°C was inter alia:

1) to compare the results obtained by standardized impact tests,
2) to compare the empirical correlations for determination of FATT from the results of SP tests
3) to compare results of SP tests obtained for the Super heater outlet header (SH) exposed for 90 000 hours at 540°C and outlet steam piping exposed for 151062 hours at 540°C (CH).

2. Testing material

A pipe ø 457 x 28 mm in as received state, Super heater outlet header (SH) ø 521x 36 mm exposed for 90 000 hours at 540°C and Output steam piping ø 324 x 48 mm exposed for 151062 hours at 540°C made of low alloy steel of type 14MoV6-3 were used as the testing materials. Chemical composition of the testing materials is shown in Table 1.

Table 1 Control chemical analysis

	C	Mn	Si	S	P	Cr	Mo	Ni	V	Al	N
AS	0,12	0,57	0,19	0,005	0,009	0,57	0,52	0,08	0,32	0,020	0,013
SH	0,14	0,64	0,29	0,009	0,013	0,51	0,59	0,17	0,33	0,005	0,010
CH	0,13	0,58	0,26	0,016	0,014	0,68	0,43	0,17	0,31	0,028	0,009

Note) AS- tube in as received state, SH-Super heater outlet header, CH-outlet steam piping

Metallurgical quality of the testing materials has been expressed by BRUSCATO factor X= (10.P+5.Sb +4.Sn+As)/100 and J factor J = (Si + Mn) x (P + Sn) x 10^4 (see Table 2).

Table 2 Metallurgical quality of the testing materials

Pipe ø457x28 mm in as received state	X = 12,0 ppm	J = 114
Super heater outlet header (SH)	X = 26,4 ppm	J = 223
Output steam piping (CH)	X = 17,8 ppm	J = 160

Segments of the size 405 x 70 mm, cut from the pipe in as received state, were heat treated by 7 different regimes (HT) (see tab. 3) to obtain significantly different yield stresses, tensile strengths and FATT.

Table 3 Selected regimes of heat treatment of testing segments

HT1	940°C/1 hour/water + 720°C/2 hours/air
HT2	940°C/1 hour/furnace +720°C/2 hours/air
HT3	940°C/ 1 hour/oil + 720°C/2 hours/air
HT4	940°C/1 hour/air + 720°C/2 hours/air
HT5	940°C/1 hour/water + 700°C/2 hours/air
HT6	940°C/1 hour/air + 740°C/2 hours/air
HT7	940°C/1 hour/oil + 740°C/2 hours 40 min./air

Charpy V notch test specimens oriented in T-L direction and semi- products of SP disc specimens 8 mm and 10 mm in diameter and 0.65 mm in thickness oriented in R-L direction were manufactured for both laboratories in mechanical workshop of MATERIAL & METALLURGICAL RESEARCH Ltd (MMR).

3. Results of impact tests

Impact tests were carried out in both laboratories at the same temperatures for each test material under investigation. The percentage of shear fracture %SF were was expressed in MMR in the form

$$\%SF = A\,x\,(1 + tgh\,(\frac{C\,x\,t+B}{C}) \qquad (1)$$

where t is test temperature in °C, A, B, C are the constants.
The percentage of shear fracture in MSA was expressed in the form

$$\%SF = A_2 + \frac{A_1\text{-}A_2}{1+e^{(t\text{-}t_o)/dt}} \qquad (2)$$

where t is test temperature in °C, $A_{1,}$ A_2 , t_o are the constants.

Tab. 4 FATT calculated from the results obtained in both laboratories

Status	FATT [°C]	
	MMR	SME
as received	-5	±0
after HT1	-72	-85
after HT2	-22	-28
after HT3	-46	-41
after HT4	-10	-8
after HT5	-12	-20
SH	+71	+60
CH	+36	+39

FATT is significantly affected mainly by metallurgical quality of the material and in the case of material in as received state by applied heat treatment.

4. Small Punch tests

Test specimen preparation was carried out in each laboratory in accordance with the Codes [1,2]. Disc specimens 8 mm in diameter and 0.5±0.005 mm in thickness were used in MMR, disc specimens 10 mm in diameter and 0.5±0.005 mm in thickness were used in SME. The screw-driven testing machines were used in both laboratories (Lab Test 5.10) with a capacity of 5 kN at MMR, CSS 44000 with a capacity of 20 kN at SME. The testing rigs (see Fig.1) with the lower die hole diameter D = 4 mm, puncher with punch tip diameter 2.5 mm and 2.0 mm (at MMR) and steel ball diameter 2.5 mm with the hardness greater than 60 HRC (at SME) were used for SP tests in the temperature range -193°C to ambient temperature.

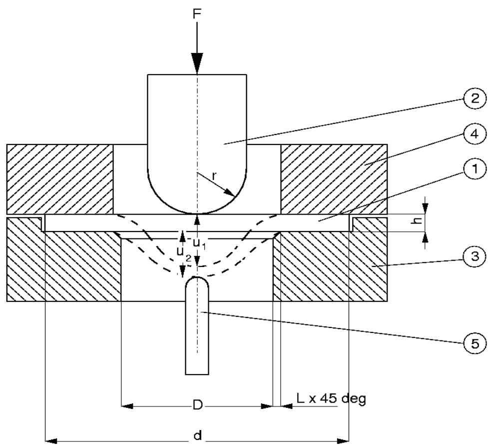

Fig. 1 Cross - sectional scheme of the testing rig (1–specimen, 2–punch, 3–receiving die, 4–clamping die, 5– deflection measurement rod).

SP tests at both laboratories were carried out under crosshead control at crosshead speed of 1.5 mm/min. The objective of the tests was to produce a load-crosshead displacement records (see Fig. 2), which contain information about the elastic-plastic deformation and strength properties of the material.

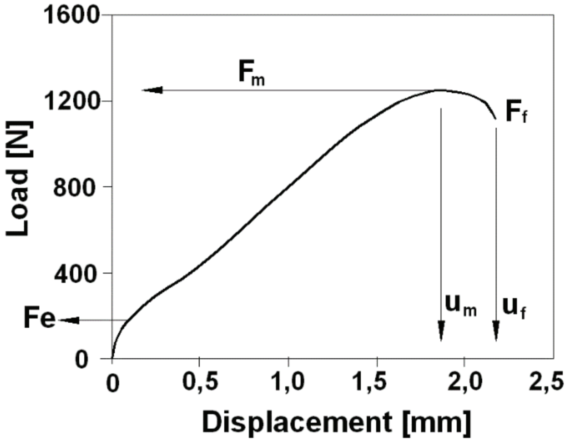

Fig. 2 Load-displacement curve recorded during a small punch test of a ductile material

The SP fracture energy E^{SP} is defined by the area under the load - displacement curve up to the displacement at onset of failure u_f which is defined as the displacement at 2% load drop after maximum load $F_f = 0{,}8 \times F_m$. FATT (Fracture Appearance Transition Temperature) is calculated from the SP test results using empirical correlation between T_{SP} (SP transition temperature), determined from the temperature dependence of fracture energy E_{SP}, and FATT determined from the results of Charpy V notch Impact tests. Empirical correlations are based on the fact that steels exhibiting standard CharpyV notch Impact ductile to brittle transition behaviour also show this behaviour during a small punch test, but usually shifted to a lower temperature [4]. SP transition temperature T_{SP} is determined as the temperature where E^{SP} has its mean value of the highest and the lowest values in the transition region, by intersecting the smooth curve fitted from the energy versus temperature data [1]. The effect of punch tip diameter (d = 2.0 mm, d = 2.5 mm) on temperature dependence of SP fracture energy was also determined in laboratory of MMR.

Fig. 3 shows the effect of punch tip diameter on the temperature dependence of the SP fracture energy E^{SP} determined for 14MoV6-3 steel in as received state in laboratory of MMR, Ltd. It is evident, that the change of punch tip diameter from 2.0 mm to 2.5 mm does not affect the temperature dependence of SP fracture energy in the transition region because the load – displacement curves are modified by punch tip radius especially at temperatures at which the ductile fracture is the dominant fracture mode [5].

Tab. 5 shows the FATT and SP transition temperatures T_{SP} obtained in both laboratories for the low alloy steel 14MoV6-3 steel in as received state and after long term exposition at 540°C.

Tab. 5 results of Charpy V Impact tests and SP tests obtained in both laboratories

	MMR		SME	
14MoV6-3 steel	**FATT [K]**	**T_{SP} [K]**	**FATT [K]**	**T_{SP} [K]**
as received state	268	96	273	97
after HT1	201	82	188	80
after HT2	251	89	245	94
after HT3	227	87	232	
after HT4	263	94	265	92
after HT5	261	96	253	96
after exp. 90 000 h	344	112	333	113
after exp. 151 062 h	309	107	312	109

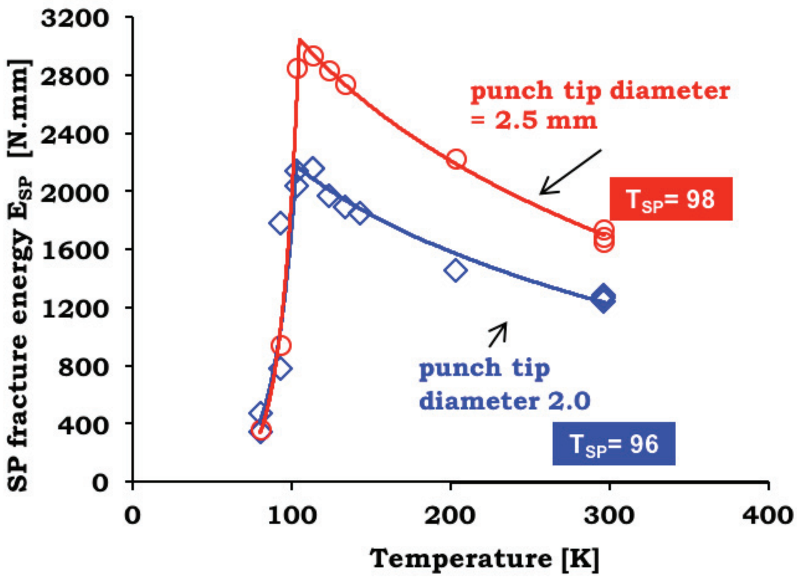

Fig. 3 The effect of punch tip diameter on the temperature dependence of the SP fracture energy E^{SP} determined for 14MoV6-3 steel in as received state in laboratory of MMR.

SP tests in laboratory of MMR were carried out using puncher 2.0 mm in diameter, SP tests in laboratory of SME were carried out using steel ball 2.5 mm in diameter.

Fig. 4 shows the empirical correlation between FATT and T_{SP} obtained for 14MoV6-3 steel in as received state and after long term exposition at 540°C. Unlike the empirical correlations for determination of yield stress and tensile strength [6] the empirical correlation for determination of FATT, obtained for 14MoV6-3 steel in both laboratories, is not affected by the stiffness of loading system (testing machine, loading rig and punch tip diameter).

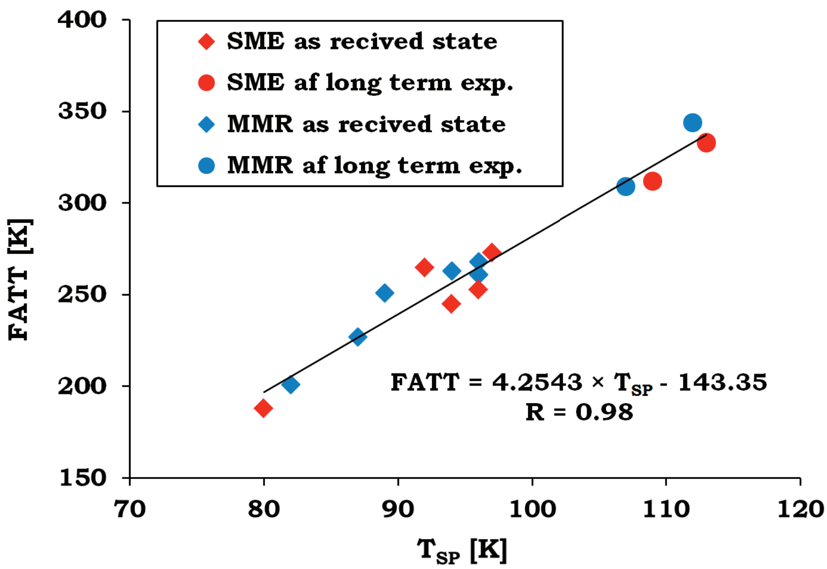

Fig. 4 Empirical correlation between FATT and T_{SP} obtained for 14MoV6-3 steel

5. Conclusions

- The change of the punch tip diameter from 2.0 mm to 2.5 mm does not affect the temperature dependence of fracture energy in the transition region because the load – displacement curves are modified by punch tip radius especially at temperatures at which the ductile fracture is the dominant fracture mode.

- The shift of the SP transition temperature due to long term exposition at 540°C is, in comparison to material in as received state, significantly lower than the shift of FATT temperature determined by standardized Charpy V test specimens.

- The empirical correlation for determination of FATT, obtained for 14MoV6-3 steel in as received state in both laboratories, is not affected by the stiffness of loading system (testing machine, loading rig and punch diameter).

Acknowledgements

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